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HANDLING COLLISION DEBRIS IN QUAD- AND DIPOLE-FIRST LHC IR OPTIONS *

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Abstract

Detailed MARS15 Monte Carlo energy deposition calculations are performed for two main designs of the LHC interaction regions (IR) capable to achieve a luminosity of 10^{35} cm^{-2} s^{-1}: a traditional quadrupole-first scheme and the one with a dual-bore inner triplet with separation dipoles placed in front of the quadrupoles. It is shown that with the appropriate design of the Nb3Sn magnets, IR layout and a number of protective measures implemented, both schemes are feasible for the LHC luminosity upgrade up to 10^{35} cm^{-2} s^{-1}.

INTRODUCTION

At the LHC at a nominal luminosity of 10^{34} cm^{-2} s^{-1}, pp-collisions at the IP1 and IP5 IRs will generate a power of almost 900 W per beam, the majority of which is directed towards the low-β insertions in the form of the collision products, with about one third of the power carried out by neutrals in the very forward direction. The final-focus magnet fields sweep the secondary particles into the coils along the vertical and horizontal planes, giving rise to a local peak power density ε_{max} that can exceed the quench limits and reduce the component lifetime, with dynamic heat loads exceeding the cryogenics capacity [1, 2]. After the LHC operates for several years at the nominal luminosity, it will be necessary to upgrade it for a higher luminosity [3], because of the physics needs and a limited lifetime of the IR quadrupoles due to the above radiation effects. Two main schemes are under consideration for the upgrade IR: a traditional quadrupole-based inner triplet, and a dipole-first layout followed by a dual-bore inner triplet [4-6].

This paper summarizes results of our thorough optimization studies of both the layouts aiming at mitigating deleterious energy deposition effects in the Nb_3Sn superconducting magnets to the acceptable levels at the upgrade luminosity of 10^{35} cm^{-2} s^{-1}. All the calculations are performed with the current version of the MARS15 code [7]. In these studies, all the energy deposition related design constraints are obeyed. These include [1]: quench stability, radiation damage, dynamic heat loads, hands-on maintenance and corresponding engineering constraints. The quench limit accepted for the Nb_3Sn IR magnets is 5 mW/g, that – with a required safety margin of a factor of 3 – gives the design goal for the peak power density averaged radially over the superconducting cable in the coils ε_{max} = 1.7 mW/g [2]. A half-crossing angle at the IP is 0.212 mrad.

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QUADRUPOLE-FIRST IR

Nb3Sn Quadrupole Inner Triplet

A comprehensive energy deposition study for a Nb_3Sn 200 T/m quadrupole inner triplet at the luminosity of 10^{35} cm^{-2} s^{-1} has recently been performed for various coil diameters, spacers in the coils, thicknesses and materials of the inner absorber (liner) [8]. The MARS15 model of the layout is shown in Fig. 1.

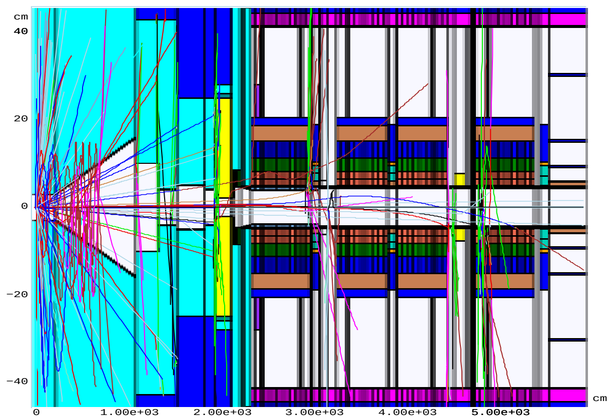

Figure 1: MARS15 quadrupole-first IR model with particle tracks (E>100 MeV) for a 7x7 TeV pp-event.

The coil apertures studied were 90, 100 and 110 mm. It was shown that:

- Dependence of ε_{max} on the coil aperture is weak and different in different quadrupoles; ε_{max} stays about the same or slightly decreases with the aperture in all quads but the second one (Q2A); ε_{max} is above the design limit by up to a factor of three in all the quadrupoles with expected lifetime of about 1.5 years with materials used in the current magnets.
- With a few millimeter thick aluminum spacers at mid-planes along the entire coil length one can reduce ε_{max} to about 2 mW/g – slightly above the design goal; the coil design and field quality are non-trivial in such an approach.
- Increasing the liner thickness helps reduce ε_{max}; a stainless steel liner thickness required to reach the energy deposition design limits is 11.2 mm in Q1 and 5 mm in three other quadrupoles (in addition to the beam screen and cold bore); it seems that it would be quite difficult to provide such an extra room.

- Using a tungsten-rhenium alloy liner instead of a steel liner and cold bore is quite promising, especially in Q2 and Q3 quadrupoles; the design goal is achieved with a thickness of a tungsten-based liner of 7.2 mm in Q1 and 1 mm in the rest of the triplet; a tungsten cold bore adds 1.5 mm to that; the configuration is compatible with the 100-mm coil aperture.

The bottom line is that an inner triplet based on Nb_3Sn 200 T/m quadrupole magnets is feasible at the luminosity of up to 10^{35} cm^{-2} s^{-1}. Note that a selection of appropriate radiation-resistant materials for these magnets and dynamic heat loads to the cryogenic system (which are 10 times as high as those at the nominal luminosity) become the outstanding issues.

Reducing L*

The luminosity can be slightly increased by reducing a distance L* of the inner triplet to the IP. An effect of a possible reduction of L* on energy deposition in the quadrupoles was studied in detailed MARS15 simulations. Two distances of the Q1 quadrupole were considered, L* = 19.5 and 17.4 m, in comparison to the baseline case of L* = 23 m. The quadrupole positions and their lengths were adjusted appropriately [9]. The 100-mm coil aperture quadrupoles with a tungsten-based liner described in a previous subsection were considered. In these runs, the total liner and cold bore thickness was 7.7 mm in Q1 and 1.5 mm in the rest of the triplet, 1 mm thinner than required for the luminosity of 10^{35} cm^{-2} s^{-1}. Fig. 2 shows longitudinal distributions of ε_{max} in the inner coils for three values of L*. There is a reduction of the peak power density at the first longitudinal maximum in the Q2A quadrupole and some increase in the β_{max} region in Q2B, both being purely geometric effect, taking into account the quadrupole shadowing by the front TAS absorber.

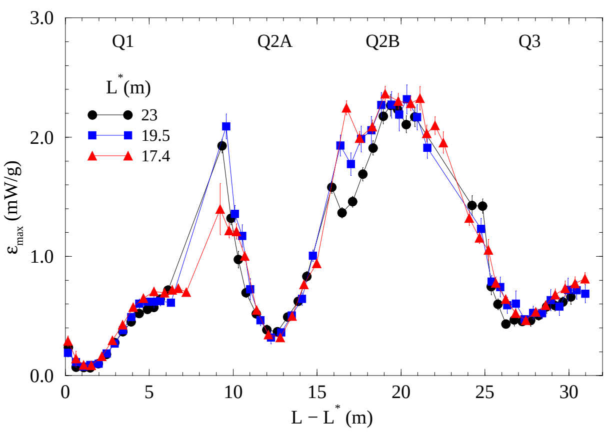

Figure 2: Peak power density in the inner coils along the 100-mm aperture triplet quadrupoles with a tungsten-rhenium liner at the luminosity of 10^{35} cm^{-2} s^{-1} for three distances L* to the IP.

Corresponding dynamic heat load distributions in the inner triplet quadrupoles are presented in Fig. 3. Not a surprise, the heat loads are about a factor of ten higher compared to the nominal luminosity [1]. Moving the triplet closer to the IP results in an increase of the heat loads in Q1 and Q2b and in some decrease in Q2A and Q3. Total integrated heat loads in the triplet are slightly increased with the L* reduction. They are 1.27, 1.47 and 1.56 kW for L* = 23, 19.5 and 17.4 m, respectively.

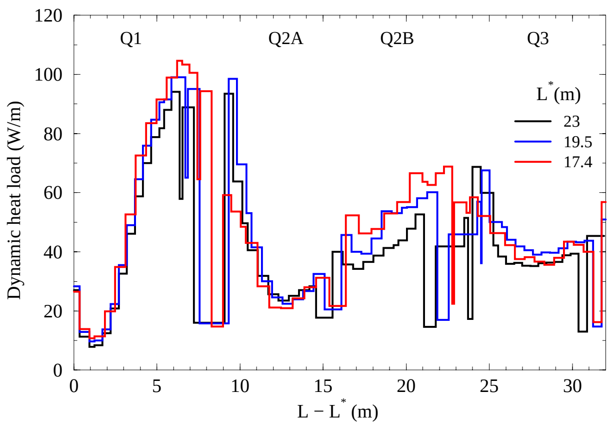

Figure 3: Distribution of total dynamic heat loads for the 100-mm aperture triplet quadrupoles with a tungsten-rhenium liner at the luminosity of 10^{35} cm^{-2} s^{-1} for three distances L* to the IP.

DIPOLE-FIRST IR

It was shown that at high luminosities, an attractive option is a dual-bore inner triplet with separation dipoles placed in front of the quadrupoles [2-6]. Compared with the baseline design consisting of single-bore quadrupoles shared by both beams, this layout substantially reduces the number of long-range beam-beam collisions, allows the beams to pass on-axis through the quadrupoles, and permits local correction of triplet field errors for each beam.

The energy deposition studies [5] were done for the separation dipole of two types: a traditional cos-theta design with a 4-layer graded coil of inner radius 65 mm and a cold iron yoke, and an open mid-plane block type coils. At the luminosity of 10^{35} cm^{-2} s^{-1}, the total power dissipated in the first dipole D1 is about 3.5 kW in either design. Peak power density ε_{max} in the cos-theta coils reaches 50 mW/g, almost two orders of magnitude higher than in the baseline LHC layout. It can be somewhat reduced via low-Z spacers in the mid-plane, being still unacceptably high. The alternative design – an open mid-plane dipole – allows absorbing much of the radiation in tungsten rods placed in the mid-plane and cooled at liquid nitrogen temperature. It was shown [5, 6] that ε_{max} can be reduced in such a design to a quite low level. It must be emphasized that such a design has never been tried, and substantial R&D on the field quality, mechanical issues and heat removal is needed before the feasibility of a magnet of this type can be demonstrated.

As a result of thorough optimization energy deposition studies, we have found that one can build an IR based on an open mid-plane block coil Nb_3Sn dipole with tungsten rods (Fig. 4), compatible with the upgrade luminosity of 10^{35} cm^{-2} s^{-1}. To achieve this goal, one needs:

- Increase the length of a copper front absorber TAS from 1.8 to 2 m.
- Split the first dipole (B=13.59 T) into two sections, D1A and D1B, 1.5 and 8.5 m long, respectively.
- Insert a 1.5-m long stainless steel absorber TAS2 in between D1A and D1B.
- Put a 3-m long copper neutral beam absorber TAN0 downstream of D1B in front of the dual-bore shell type separation dipole D2 (B=14.09 T).
- Put a 1.2-m long stainless steel absorber TAS3 upstream of the inner triplet (dual-bore 200 T/m quadrupoles).

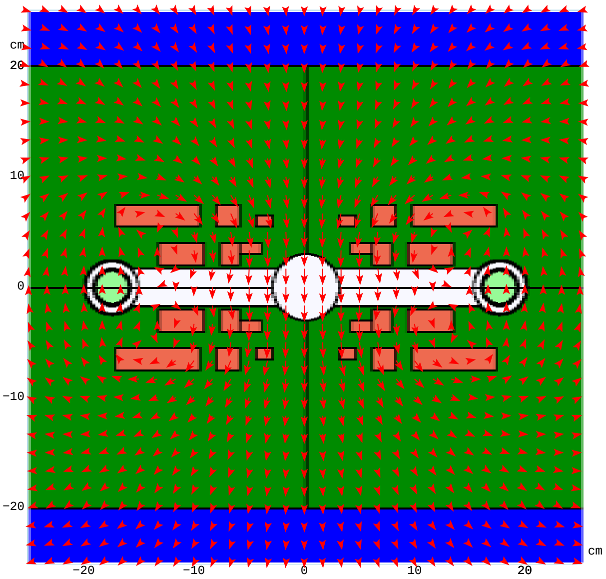

Figure 4: MARS15 model of the open mid-plane block coil Nb_3Sn dipole.

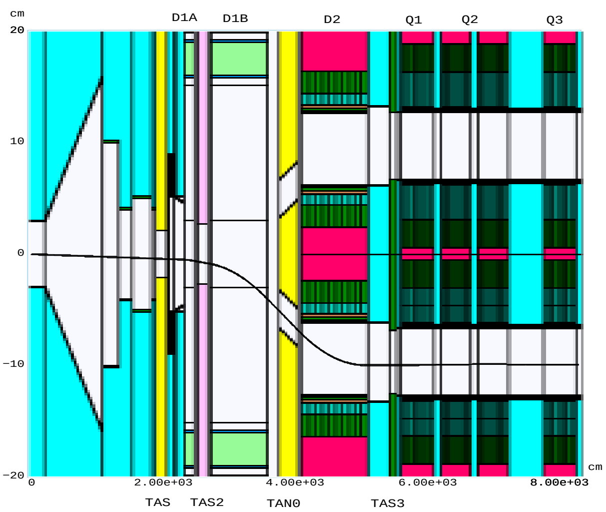

Figure 5: MARS15 dipole-first IR model with 7-TeV proton trajectories shown for the beam from IP.

This design is shown in Fig. 5. The lattice parameters are described in Ref. [9]. Fig. 6 presents charged hadron flux isocontours, illustrating how the system components work.

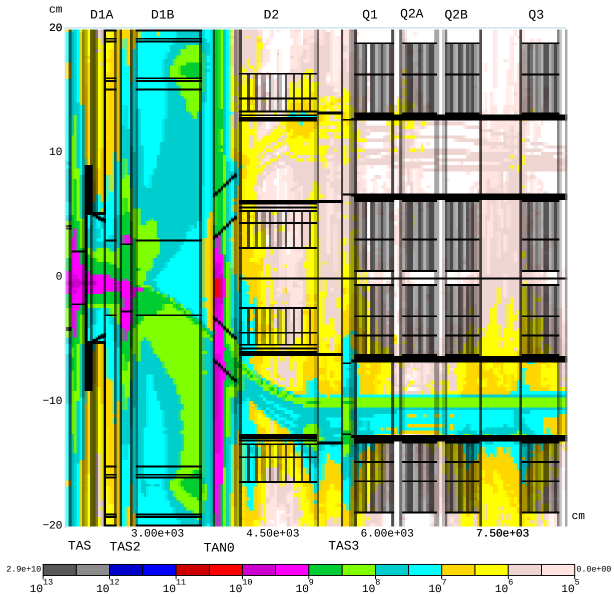

Figure 6: Charged hadron flux ($cm^{-2}s^{-1}$) isocontours in the dipole-based IR.

Power density isocontours at the hottest spots in the D1B and D2 dipoles (at their non-IP ends) are shown in Figs. 7 and 8. One can see how nicely the tungsten rods in the mid-plane in D1 and protective measures upstream of D2 do their job.

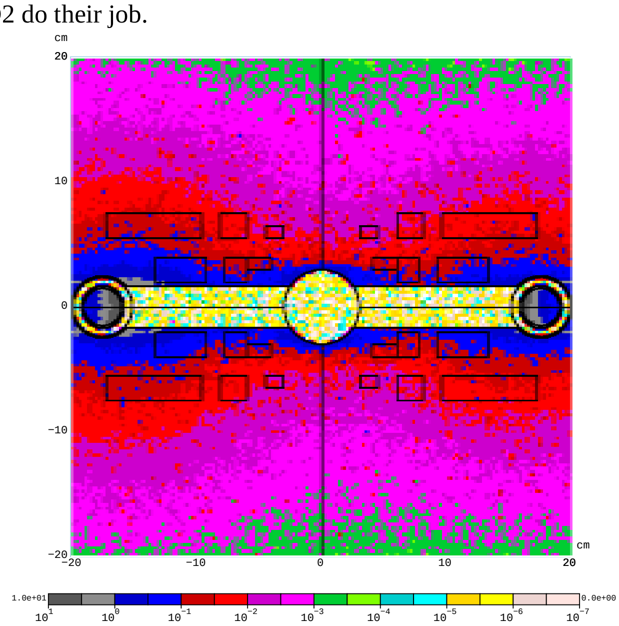

Figure 7: Power density isocontours (mW/g) at the non-IP end of the D1B dipole.

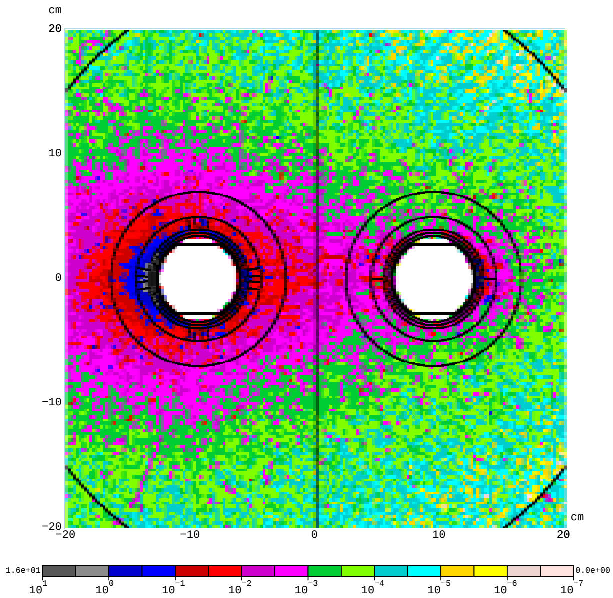

Figure 8: Power density isocontours (mW/g) at the non-IP end of the D2 dipole.

Peak power density in the D1 and D2 Nb_3Sn superconducting coils is about the same, ε_{max} ~ 1.3 mW/g, 30% below the design limit. A TAS3 collimator in front of the Q1 quadrupole brings ε_{max} below the design limits in the entire triplet (see Fig. 9), and allows using a NbTi superconductor technology for the quadrupole coils, with a component lifetime of many years. Dynamic heat loads to the most important components in the region are 1.75 kW in TAS, 0.5 kW in D1, 3.94 kW in TAN0, and 0.11 kW in the D2 through Q3 magnets. As Fig. 10 shows, the inner triplet quadrupoles experience even lesser loads than the ones in the nominal LHC case.

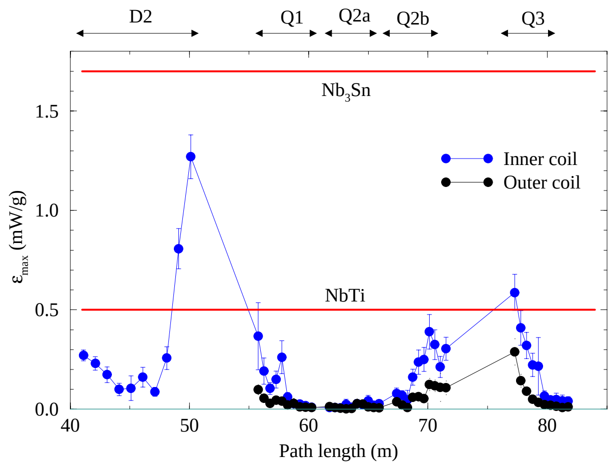

Figure 9: Peak power density in D2 through Q3 region.

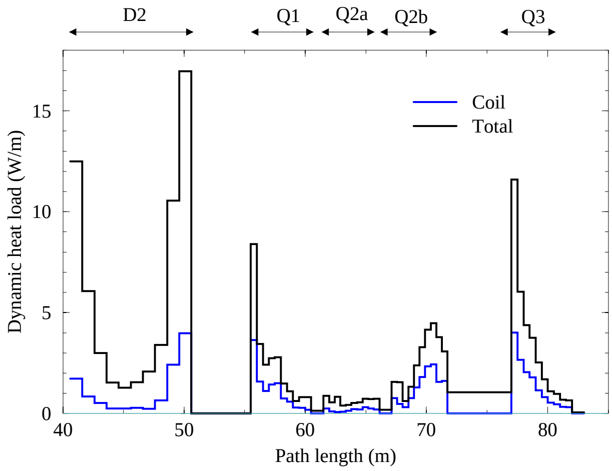

Figure 10: Dynamic heat loads in D2 through Q3 region.

CONCLUSION

Based on realistic MARS15 energy deposition modelling it is shown that both quadrupole- and dipole-first layouts are feasible for the LHC luminosity upgrade up to 10^{35} cm^{-2} s^{-1}. Appropriate R&D is needed in order to address kW-levels of dynamic heat loads on the IR cryogenic system and selection of materials to be used in a new generation of Nb_3Sn magnets.

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